Human Factors of Integrated Systems Health Management on Next-Generation Spacecraft

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Abstract

A shuttle crew's ability to manage the health of the spacecraft systems is compromised by the limited capabilities of the onboard health management technologies, many of which date from the 1970s and 1980s. Most notably, the Caution and Warning system does little more than generate auditory alerts and fault messages in response to out-of-limit sensor readings. Today's health management technologies have much more extensive capabilities that range from detecting off-nominal trends and data patterns to executing fault isolation and recovery procedures. On next-generation spacecraft, these technologies could be harnessed to replace the traditional Caution and Warning system with a decision and action support system that assists the crew with all aspects of real-time health management operations. We discuss several aspects of the design of such a system, including human-machine functional allocations; user interfaces to enable and support human-machine interaction, and methodologies for testing and evaluating collaborative operational concepts and associated user interfaces.

Introduction

Sending people into space ranks among the riskiest and most challenging endeavors of our time. Much of the challenge stems from the fact that human-rated spacecraft consist of very complex and often highly interconnected engineering systems, including propulsion systems; electrical and mechanical power generation and distribution systems; guidance, navigation, and control (GN&C) systems; data processing systems; life support systems; and communications systems. Particularly during the dynamic phases of a space mission, such as launch, ascent, and entry, these systems must perform to precise operational specifications in very harsh environments, whose cumulative effects on system functioning are often poorly understood. As a result, systems malfunctions are an ever-present threat to mission success and crew safety.

To minimize this threat, a significant fraction of real-time mission operations is devoted to monitoring, managing, and maintaining the health of the onboard systems. Each system is heavily instrumented with sensors that provide real-time numeric readings of critical operating parameters, such as temperatures, pressures, accelerations, and flow rates. If the values from any one of these sources move outside a range consistent with normal systems operations, the "out-of-limits" condition must be detected, the cause must be identified and, if the cause is determined to be a system malfunction, the appropriate remedial actions must be taken.

Figure 1 captures the series of events that accompany a systems malfunction from the perspective of a crewmember in the shuttle cockpit (for simplicity, the figure excludes ground-based activities and crew-ground communications). The vehicle's Caution and Warning (C&W) System, described in greater detail below, detects an off-nominal sensor reading, sounds an alarm, and generates a flashing fault message on one or more cockpit displays. The crewmember first silences the alarm by pressing a master alarm button, and then stabilizes the fault message by pressing the "acknowledge" key on the cockpit keyboard. He or she then reads the fault message (or several messages if the problem has "daughter" faults associated with it), and determines which message pertains most closely to the root cause of the problem. Using the selected message as an index, the crewmember then locates the appropriate fault management procedures in a paper "flight data file" (FDF) or cockpit cue card. These procedures typically take the form of one or more manual switch throws that change the operating mode of the system.

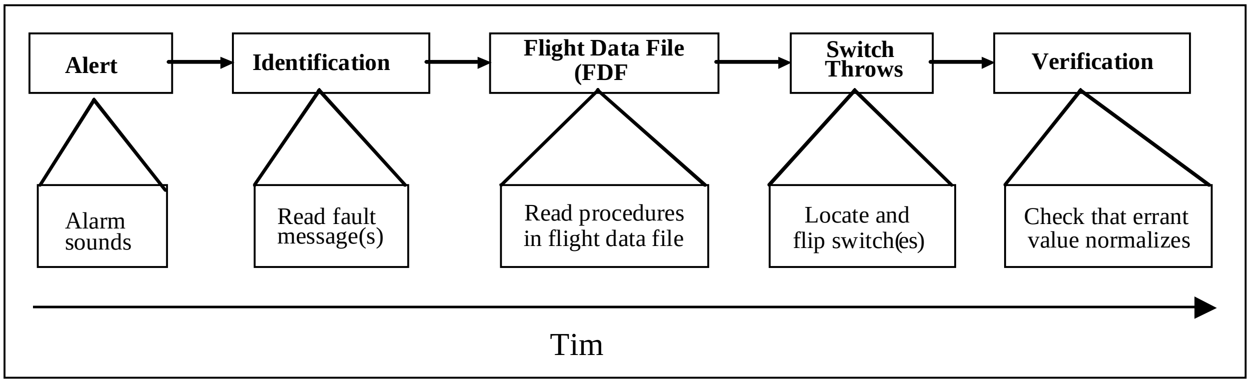

Figure 1. Typical Sequence of Shuttle Fault Management Operations.

Complicating Factors

Although these activities may sound straightforward, each one is impacted to greater or lesser degrees by a variety of complicating factors. These factors include:

Data availability. The most basic requirement for effective fault management is adequate situation awareness of systems mode and systems functioning. Sensor data is the primary source of this awareness. On the shuttles, however, only a small subset of the sensed data is included in the data bus connecting the orbiter instrumentation system with the cockpit. Furthermore, in the original version of the cockpit, much of the data could only be viewed on one of three cathode-ray tube (CRT) screens, meaning that an even smaller subset of the data was visible at any one time. If a crewmember wanted to view all available data for a particular system, he or she had to navigate through several successive display formats. Starting in 2000, the CRT's on some of the orbiters were replaced by liquid-crystal display (LCD) screens as part of a "glass cockpit" upgrade. The cumbersome display navigation requirements for accessing systems data were largely unaffected by the upgrade, however.

Cockpit display formats. For the most part, the display formats available for viewing on the new LCD screens are replicas of the original display formats designed for the CRTs. These "legacy" formats are often poorly organized and highly cluttered, taking the form of closely spaced tables of monochromatic (green) alphanumerics. An example is the "BFS GNC SYS SUM 1" display on the left side of Figure 2. The format makes it difficult to localize and process key sources of information, such as off-nominal sensor readings. More importantly, as shown in the "zoomed-in" section in the lower left section of the figure, digital values are a notoriously inefficient way to convey information about systems mode and systems functioning. Crewmembers are not so much interested in the actual values themselves as in what the values convey about the operational status of the system ("Is the system functioning nominally or off-nominally?") and its current configuration (e.g., "Is Isolation Valve "A" on Leg "B" open or closed?"). To build up such situation awareness, the "raw data" on the screen has to be translated into a form that matches the crewmember's mental model of the system architecture and possible configurations.

C&W System Limitations. By today's standards, the shuttles' data processing system has only limited capabilities. During dynamic flight phases, the general-purpose computers are almost fully occupied with computations relating to vehicle guidance and flight control. The C&W system software, also housed on these computers, performs simple real-time comparisons between sensor readings and preset upper and lower values. If a set number of successive readings fall outside of these values, the out-of-limits condition is signaled to the crew by some combination of auditory and visual alarm. In addition, each out-of-limits condition is typically accompanied by a written fault message to help the crew identify the source of the problem.

Limit-sensing software is computationally straightforward, making it both robust and relatively easy to flight certify. Functionally, limit-sensing software automates much of the information processing

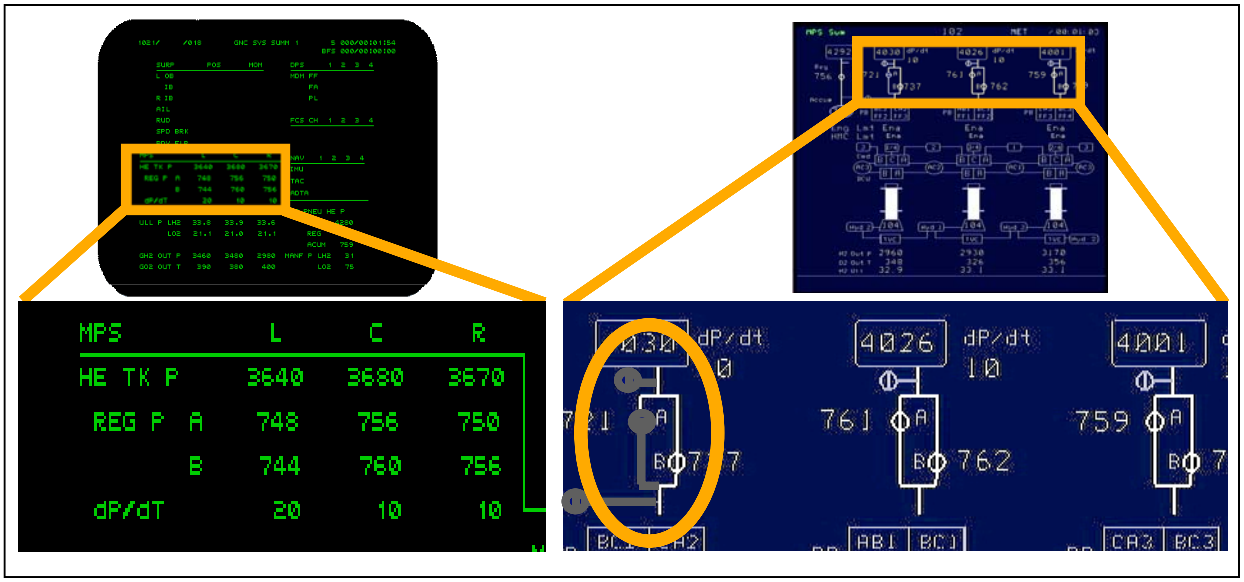

Figure 2. The left side depicts the BFS GNC SYS SUM 1 display format from the current shuttle cockpit. The upper panel shows the entire display; the lower panel zooms in on the area depicting data on the helium supply systems for the main engines. The right panels depict the MPS Sum display designed for the CAU project. The upper panel depicts the entire display. The lower panel zooms in on the graphical elements depicting the helium supply systems. See text for more details.

associated with parameter monitoring and detection of off-nominal readings. In a vehicle as complex as the shuttle, instrumented with over 2000 individual sensors, these activities would otherwise completely overwhelm the crew. At the same time, however, the "single-sensor, single-annunciation" interface with the software creates a serious human factors problem. The original motivation behind the interface was to maximize the crews' situation awareness by providing them with as much information as possible about subsystem malfunctions and component failures. However, because the software processes each data source independently, the system has no ability to discriminate a legitimate off-nominal reading from a spurious signal from either a failed sensor, or a failure in a digital signal conditioner or other component of the data processing system. More seriously, due to the complexity and interconnectedness of shuttle subsystems, a failure in one component frequently causes additional equipment and/or sensor failures, resulting in a cascade of alarms and fault messages. In many cases, the proliferation of alarms and messages makes it very difficult to identify the "root cause" of the problem (McCandless, McCann, & Hilty, 2003).

A second drawback with the current C&W system is that, having generated one or more fault messages, it provides no further assistance with the fault management process. Once a crewmember has selected a fault message, he or she must then navigate through a FDF to find the appropriate checklist of fault management procedures. The checklist, a series of specialized instructions, is written in the form of specialized symbols, abbreviations, and spatial codes (i.e., line indentations) that collectively require considerable training to decode and understand. The instructions encompass activities such as reading gauges, comparing values, and throwing cockpit switches to alter the operating mode of the affected system. In some cases the procedures are short and straightforward, as when they call for a switch from a failed primary component, such as a pump or a fan, to a healthy backup. In other cases, the instructions are considerably more complicated. For example, sometimes the fault message is itself consistent with a variety of "root cause" failures. The procedures associated with that message may first designate switch throws to reconfigure the affected system into a new operating mode that provides additional insight into the underlying problem. Once the problem is more clearly understood, additional switch throws may then be necessary to place the system into a safe state, and return as much of the system as possible to its nominal operational configuration. Importantly, these switch throws are virtually all manual; the crew has to locate the appropriate switches from the hundreds of switches in the cockpit, and then toggle them to the commanded position. These activities are both time consuming and attention-demanding, greatly disrupting crewmembers' nominal information acquisition activities (Huemer, et al., 2005).

Crew-Ground Interactions. We noted earlier that only a small subset of the sensed data could be displayed to the crew at any one time. In addition, during dynamic flight phases, the crew must time-share systems health management activities with numerous other critical mission-management requirements, such as monitoring the vehicle's attitude, velocity, and flight path. In many cases, the crew simply cannot safely devote the time and resources necessary to perform the health management activities, particularly when faced with multiple alarms and fault messages, or when faced with a malfunction (or set of malfunctions) not covered by existing procedures. To deal with these circumstances, a much larger selection of sensor readings is included in the near-real-time telemetry stream that flows from the vehicle to the Launch and Mission Control Centers (MCC). Flight controllers and systems subject-matter experts continuously monitor these data for anomalous readings. Ground software flags out-of-limit parameters, sometimes using tighter limits than those used onboard in order to detect faults more quickly. Additionally, ground software can be upgraded more easily than Shuttle software, and is thus closer to the state-of-the-art. The software does, for example, provide trending information on some main engine parameters in graphical form. Using these tools, ground controllers will typically assist the crew in disambiguating the root cause of a series of annunciations and fault messages, and also assist with determining the root cause and appropriate procedures for novel failure situations not covered in the flight data files. The crew must still locate and flip the proper switches and verify that mitigation strategies proceed as expected.

Health Management on Next-Generation Vehicles

NASA is designing a new Exploration Transportation System (ETS) to replace the aging shuttles, return humans to the Moon, and enable human exploration of more remote destinations. One of the most important drivers for the design of ETS vehicles is that they will eventually have to operate more autonomously than the shuttles. For example, once ETS vehicles start to travel beyond low Earth orbit (LEO), speed-of-light delays will combine with a lack of communications infrastructure to eliminate real-time data links and voice communications with the ground. Consequently, many critical health management operations (as well as operations that rely on health management data) will have to be performed without real-time ground assistance. Considering the large role of ground-based resources in today's fault management activities, this shift to more autonomous operations will require a considerable augmentation in onboard health management capabilities.

Enhancing onboard health management capabilities of ETS vehicles is a considerable challenge. As we have seen, managing the health of a vehicle as complex as a human-rated spacecraft requires large amounts of data-and-information processing resources. On the shuttles, neither the human or machine resources are sufficient to meet these requirements. With a maximum crew complement of four (at least for missions in the foreseeable future), ETS vehicles will have no more "pairs of eyes" onboard than the shuttles do. Furthermore, ETS vehicles are going to resemble the capsules and modules of the Apollo era. If anything, the visual real estate available for presenting systems health information will be reduced compared to the shuttles.

Current Machine Capabilities. Fortunately, in the three decades since the original shuttle design, the processing resources of computing devices have increased dramatically. Software developers in industry, government, and the applied artificial intelligence community have exploited these increases to develop "end-to-end" health management and process control systems with much more extensive capabilities than the limit-sensing and fault annunciation software on the shuttles. Figure 3 depicts a representative example of today's "state of the art" in end-to-end health management systems (Keller, Wiegand, Swearingen, Reisig, Black, Gillis, & Vandernoot, 2001); note also that a comprehensive (i.e., vehicle-level) health management architecture is likely to consist of a network of such system-level managers,

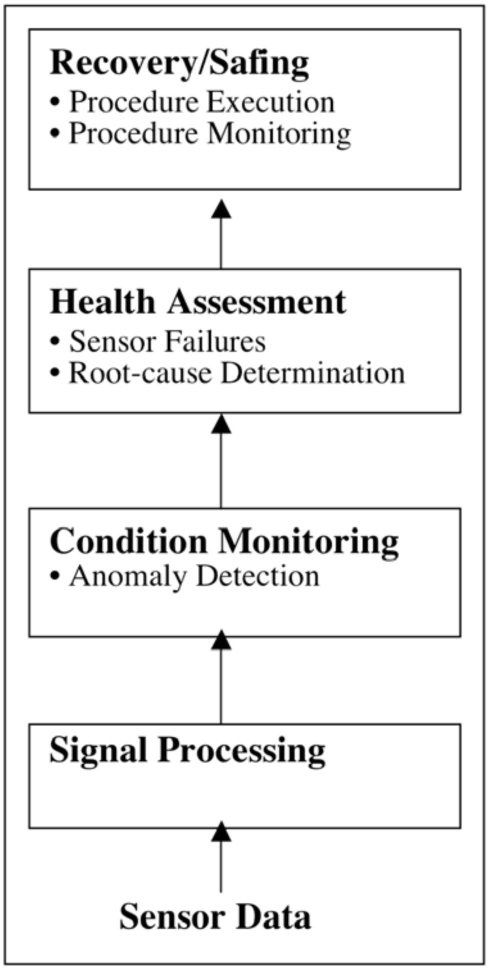

Figure 3. Representative State-of-the-Art Health Management System.

one for each significant engineering system (and significant structures) on the vehicle (Atlas, Bloor, Brotherton, Howard, Jaw, Kacprzynski, Karsai, Mackey, Mesick, Reuter, & Roemer, 1999). The architecture depicted in the figure assigns specific computational functions and capabilities to distinct data-and-information processing "layers." Starting from the bottom of the figure, the Signal Processing Layer conducts various tests on continuously varying sensor data to verify the validity of the data. The Condition Monitoring Layer then applies data-monitoring and data-mining algorithms in order to classify the time-varying data patterns (and, by extension, the current functional mode of the system) as being consistent with either nominal or off nominal operations. Then, in the Health Assessment Layer, rule-based and/or model-based reasoners (MBR's) make root-cause diagnoses of off-nominal patterns. Finally, the Recovery/Safing Layer contains a reactive planner that 1) determines what procedures are required in order to achieve the desired goal state (typically, a return to the nominal operational mode), 2) determines the correct sequence of actions to achieve that state, 3) physically commands the actions, and 4) from sensor data, determines whether the actions have been carried out and the desired goal-state achieved.

With ETS vehicles facing the same general limits on onboard human processing resources as today's vehicles, any substantial enhancement in onboard health management capabilities will clearly have to involve an infusion of these advanced health management technologies. In the following sections, we consider some of the design issues that will accompany this infusion.

Human-Machine Functional Allocation. Modern "end-to-end" health management systems have generally been designed to operate in "stand-alone" (fully automated) environments, such as an unmanned spacecraft. The health management software is wholly responsible for all aspects of systems health management, including fault detection, isolation, and recovery. On a crewed vehicle, with humans in the loop, the question of what activities should be automated and what activities should be left to the crew has to be addressed (Parasuraman, Sheridan, & Wickens, 2000). We offer the following observations on this contentious issue. First, a fully automated health management system is neither appropriate nor optimal for a crewed spacecraft. Full automation is not appropriate because health management software systems are not yet robust, reliable, and capable enough to entrust the lives of a crew; doing so would represent an unacceptable risk. Hardware and software failures are more common in space than on the ground, in part because space-based platforms are vulnerable to radiation-induced "single event upsets." Crewmembers are unlikely to trust software tools to the point where they cede all control over emergency operations.

Aside from issues of trust and reliability, full automation is not optimal for a crewed spacecraft because it does not fully utilize all available onboard resources. Crewmembers are (and should continue to be) trained in the architecture and functioning of vehicle systems to the point where they become subject-matter experts in their own right. Taking them out of the loop amounts to a decision to waste a valuable onboard source of expertise. Equally important, humans and machines bring different capabilities and different limitations to bear on the health-management process. These capabilities are frequently complementary, with the strengths of one compensating for weaknesses of the other. For example, the leading technology for automated fault diagnosis (Health Assessment Level in Figure 3) is MBR. To determine the root cause of a set of symptoms (faults or anomalies), MBR utilizes models of the systems that specify how components interact. Developing high fidelity models of complex physical systems is very difficult, and there are still issues to be resolved before MBR can offer a complete diagnostic solution. Even if a model can be developed that reacts correctly to all failure modes identified in advance, novel failures may still occur as hardware ages and undergoes sustained exposure to the launch and space environment. The model may not adequately deal with these novel failures. Moreover, because MBR is dependent on sensor placement and sensor coverage, an MBR system may not be able to completely disambiguate a set of hypotheses that explain a given set of symptoms. Humans excel (and surpass machines) in their ability to retrieve situation-appropriate information from long-term memory, to improvise and use procedures flexibly, and to exercise judgment based on common-sense (nondeterministic) reasoning. A human may have deeper insights and be able to apply knowledge from a somewhat similar situation that happened under completely different circumstances to arrive at a single root cause to a set of symptoms.

On the other hand, there are clear areas where machine capabilities greatly surpass those of humans. Machines have much greater abilities to perform highly complex operations virtually simultaneously (i.e., to perform many different computations seemingly at once), and to monitor, process, and recognize patterns in time-varying numeric data. In conjunction with today's advanced electronic display devices, machines can also retrieve, organize and display information much more efficiently than humans can accomplish without machine assistance.

Given these considerations, we believe the key to health management on next-generation space vehicles is to exploit the end-to-end capabilities of today's health management systems, not to replace the crew, but to evolve the traditional C&W system into a decision-and-action support system (DASS) that *assists* the crew with all aspects of health management operations (Scandura and Garcia-Galan, 2004). The outstanding challenge with this approach is to develop a viable operational concept that blends and coordinates the activities of the DASS with crewmembers. We turn now to some of the issues of human-machine interface design that must be addressed in order to meet this challenge. We then provide an example of a candidate operational concept for real-time fault management that illustrates these issues and offers candidate design solutions.

Guidelines For Human-DASS Teaming

Fortunately, many of the issues that should be addressed in order to achieve effective coordination of human and machine activities in a spacecraft setting are already well documented (Malin, Schreckenghost, Woods, Potter, Johannesen, Holloway, & Forbus, 1991). As applied to a DASS system, these issues include, but are not limited to:

Determining the optimal functional allocation between DASS and Crew. This determination must capitalize on the strengths and capabilities of humans and machines, thereby optimizing the capabilities of the joint human-machine system, and avoid the "out-of-the loop unfamiliarity" (OOTLUF) problem (Endsley & Kiris, 1995) that accompanies systems with too much automation. The functional allocation needs to strike a balance between the reduction in workload that DASS makes possible with the potential loss of situation awareness that can occur when DASS performs operations without sufficient human oversight and involvement. There are numerous examples from today's highly automated aircraft cockpits of serious consequences where crewmembers have been insufficiently involved in an automated operation, and are suddenly called upon to deal with the consequences of that operation (Sarter, 2001).

Generic tools to determine an appropriate level of automation across a wide variety of mission operations, including real-time fault management, are currently under development. One such tool, based on seminal work by Sheridan and his colleagues (Sheridan, 1992; Parasuraman, et al., 2000) is the Function-specific Level of Autonomy and Automation Tool (FLOAAT) under development at NASA Johnson Space Center (Proud, Hart, & Mrozinski, 2003). FLOAAT begins by decomposing task requirements to a functional level. These functions are then classified into four types conceived by Col. John R. Boyd in the 1970s as an air-to-air combat strategy for military fighter pilots. The four types are Observe – gather, monitor, and filter data; Orient – derive options through analysis, trend prediction, interpretation, and integration; Decide – rank the available options; and Act – execute the chosen option. Each type has eight corresponding levels of automation with definitions ranging from fully manual (1) to fully automated (8). For each function type, domain experts give a qualitative rating (high to low) to specifically tailored questions whose aim is to determine how much the experts trust the software to perform the function correctly and what experienced developers believe is the cost/benefit relationship of automating the function. The ratings are tallied and a numeric score is generated for the level of automation (LOA) that human operators will trust the system to be designed to, and that balances the costs and benefits of automation performing the function. These two limits are computed individually and the lower of the two limits is suggested as the function's design level of automation or autonomy.

Ensuring crew visibility into DASS functioning. Once a functional allocation has been chosen, user interfaces must be designed to support it. One of the fundamental requirements for these interfaces is that they provide crew insight into DASS functioning. "DASS functioning" has two distinct meanings. One meaning refers to any systems reconfigurations performed by DASS (as opposed to the crew), and resulting changes to system mode and system functioning. If a crewmember is included in the control loop in any capacity, she (or he) must be able to quickly synchronize her mental model with the actual state of the system in order to address the detected failures and assist with recovery actions. In some situations, automatic forms of compensatory control can hide faults and failures until they are almost beyond the operator's ability to recover. It is very important in such cases that the compensatory actions are transparent to the operator, to allow for earlier intervention or for planning a recovery strategy.

The second meaning of DASS functioning refers, not to the overt actions of the system per se, but to the algorithms and computations that underlie those actions. Following Billings (1997), automation is deemed "clumsy" if the underlying algorithms that support machine-based decision-making and action taking are opaque to the human. User interfaces are needed that allow the crew to make continuous determinations such as, "Is DASS itself "healthy"? Is the system performing in a manner consistent with what I know about its functionality, the kinds of computations it should be performing, and the outcomes of those computations?"

Backup and Redundancy Requirements. We have already noted the particular vulnerability of spacecraft systems to subsystem failures and malfunctions. At the hardware level, these vulnerabilities generate stringent requirements for backup capabilities and functional redundancies. The same considerations extend to a safety-critical software system such as DASS, and place additional requirements on the design of the crew-DASS system.

Hardware/Software Redundancy. On the shuttle, ascent and entry guidance, navigation, and flight control functions are almost fully automated. A failure in either the flight software itself, or in the hardware on which the flight software is housed, would put the mission in immediate jeopardy. Fully recognizing this vulnerability, the original shuttle designers had separate contractors develop independent flight software systems. One company's software was designated as primary, the other as backup. The primary software system, housed on four of the five onboard general-purpose computers, has nominal control over the vehicle. If the primary system fails, due to some combination of software or computer failure, the backup system, housed on the fifth computer, can provide the most essential flight control functions.

There is an important user interface element illustrated by this redundancy. The two software systems continuously and independently compute critical flight parameters (e.g., vehicle attitude) that the backup system requires in case the crew has to engage it. In addition, at two minutes into ascent, additional guidance parameters (e.g., the exact time of main engine shut down to achieve the targeted orbit insertion point) are computed redundantly. These values, along with any real-time discrepancies between the systems' computations of vehicle attitude, are displayed continuously to the crew. By crosschecking these values, the crew can assess the health of each software system and the veracity of its navigation and guidance computations. As we move into a next generation vehicle, where DASS is responsible for a much larger proportion of health-related data and information processing activities than today's C&W system, similar software and hardware redundancies may need to be built into the DASS system to provide similar opportunities to crosscheck DASS functioning.

Crew as Backup. Redundancy requirements do not stop with the hardware and software. To protect against a general breakdown in the data processing system (or critical component), the crew should retain as much capability as possible to perform DASS functions manually (ideally, the reverse would also be true; DASS should be able to act as backup in the event of a crewmember "malfunction." We shall return to this rather tricky issue when we discuss adaptive cockpits in the next section). Of course, at the data processing level (Level 1 in Figure 3), this requirement is unobtainable; three or four crewmembers simply do not have the capacity to monitor and detect anomalies in thousands of data sources, even if all the data could be displayed simultaneously. On the other hand, crews today perform virtually all the physical actions, predominantly switch throws, called for in the fault management procedures. In principle, these purely physical actions could be automated (see below). But this approach exposes a human factors conundrum. In order to function effectively as a backup, a crewmember must retain the skill set needed to perform nominally automated functions. If a procedure or operation is always automated, crewmembers will not get a chance to perform it, and will lack the skill set necessary to serve as backup if the need arises. This issue could be resolved through extensive training on scenarios that simulate DASS failures and require a reversion to manual operations. Another option is to design the crew-DASS functional allocation and supporting interfaces in such a way that, although the automation actually performs the operation, allowing the workload-reduction benefits of the automation to be realized, the human is kept "in the loop" in a manner that continuously reinforces the skill set necessary to perform the function manually. In the next section, we describe one option that follows this "continuous reinforcement" approach.

Candidate DASS for Next-Generation Space Vehicles

The "state-of-the-art" health management system described in Figure 3 has the ability to automate virtually all of the fault management activities currently performed by the crew and/or ground personnel (Figure 1). Mindful of the human factors risks of over-automation, McCann and McCandless (2003) argued for a functional allocation between crew and health management system that would give the automation responsibility for data monitoring, detecting off-nominal conditions, making root-cause failure diagnoses, and retrieving and executing the appropriate procedure(s). The crew would maintain overall control of the process, however, by having to give the automation "permission" to execute each individual fault management procedure in the (now electronic) FDF. In this section, we describe a candidate crew-DASS system based on this particular functional allocation. The candidate provides a platform from which to describe user interfaces and operational concepts that follow the functional allocation determination, and begins to address some of the design requirements for a Crew-DASS system identified earlier in the paper.

Making DASS Activities Transparent to the Crewmember: System Summary Displays. A central design requirement is for user interfaces that enable crewmembers to precisely track changes to the functional mode of a system that accompany DASS actions. This would be quite difficult with the current shuttle system summary displays, as they do not make the current operating mode transparent to an observer. Fortunately, these display formats were the target of a recently completed Cockpit Avionics Upgrade (CAU) redesign by teams of NASA astronauts, mission operations, and human factors personnel. The redesigned displays, described by McCandless, Hilty, & McCann (2005), consolidate systems information onto individual, task-oriented systems summary displays, eliminating the need to navigate through several displays to acquire systems information. More importantly, the displays incorporate many of the synoptic features of systems displays in modern glass cockpit aircraft, organizing graphical depictions of system components, such as valves, tanks, and flow lines, around a spatial arrangement that emulates key aspects of the underlying system architecture. In addition, CAU designers incorporated luminance and color-coding schemes into the graphics so as to provide "at-a-glance" information concerning current system configuration and operating mode.

An example of these changes is the redesigned Main Propulsion System (MPS) Summary Display, shown on the right side of Figure 2. The zoomed-in section on the bottom right section of the figure shows the graphical depiction of the helium supply system for the shuttle's three main engines (essentially, this is the redesign of the section of today's BFS GNC SYS SUM 1 display shown on the lower left). Our working assumption is that system summary displays on next generation vehicles will resemble the CAU redesigned displays much more than they will resemble existing shuttle displays. For that reason, the CAU displays will form the point of departure for our discussion of candidate Crew-DASS interfaces.

The next major requirement for DASS displays is that they provide insight into the health and functioning of the DASS even when all systems are functioning nominally. Consider, first, how we might provide insight into the functions associated with the Condition Monitoring level in Figure 3. On CAU System Summary Displays, sensed values are normally shown in white. If a value moves beyond its Caution and Warning software limits, the out-of-limits value is signaled by changing the color to either yellow or red, and presenting a yellow or red "up" or "down" arrow (or other symbol) beside it. By contrast, the DASS Condition Monitoring level would contain much more sophisticated data processing algorithms such as time series analyses of the fluctuations (variance) in sensor readings over time. These fluctuations are a normal constituent of complex systems operations, and mathematical analyses of the fluctuations can be a powerful tool for classifying nominal versus off-nominal modes of system functioning (Huff, Tumer, & Moser, 2001). During nominal systems operations, these algorithms will be operating covertly, in the background as it were. It would be highly desirable to provide a means of continuously informing the crew that these classification algorithms are "alive and well" and actively performing their function.

One design concept to meet this requirement would be to first characterize the variability in sensor values that is consistent with nominal systems operations (similar to the bandwidth used to assign upper and lower limits in a limit-sensing system). During times of systems operation, the current sensor readings on the system summary displays would appear in grey, and variance in the readings over time would be accompanied by physical changes in the intensity and/or color of the depicted values. Variance consistent with nominal operations would be accompanied by subtle changes in the brightness of the parameter (a step up in brightness when the value increases, and a step down when the value decreases). Since these changes would only affect brightness along the grey scale, they would give the user "at-a-glance" indications that DASS was classifying the current variability as consistent with nominal systems operation, and also that the DASS algorithms were "live", processing the data and performing the nominal/off-nominal classification in real time. If, at some point, the algorithms determined that the changes were consistent with the beginning of a deviation from nominal functioning, all of the sensed values contributing to that assessment would change to the warning color, typically yellow. Yellow values would signal that an abnormal trend has been detected; the values would change to red once the abnormal condition was confirmed. In this scheme, color-and-intensity coding would change from today's system, based only on limit sensing, to a scheme that communicates information about computations that are integrating information across both time and individual sensors.

The next algorithmic layer is Health Assessment, where the root-cause of an off-nominal data pattern is determined. Again, we would like our user interface to convey some indication of the reasoning behind root-cause failure determinations. However, this issue is complicated by the plethora of algorithms and computations employed by different reasoners. Some are model-based, others rule-based, while still others take a sensor-fusion approach that subtracts expected (nominal) values from the current readings, and then matches the pattern of residuals against known failure modes. Since the user interface will be highly dependent on the specifics of these computations, we will not attempt to provide a generic interface example here.

The final DASS level is Procedure Retrieval and Execution. From the perspective of a "permissions-based" crew-DASS functional allocation, this level involves the tightest interactions between

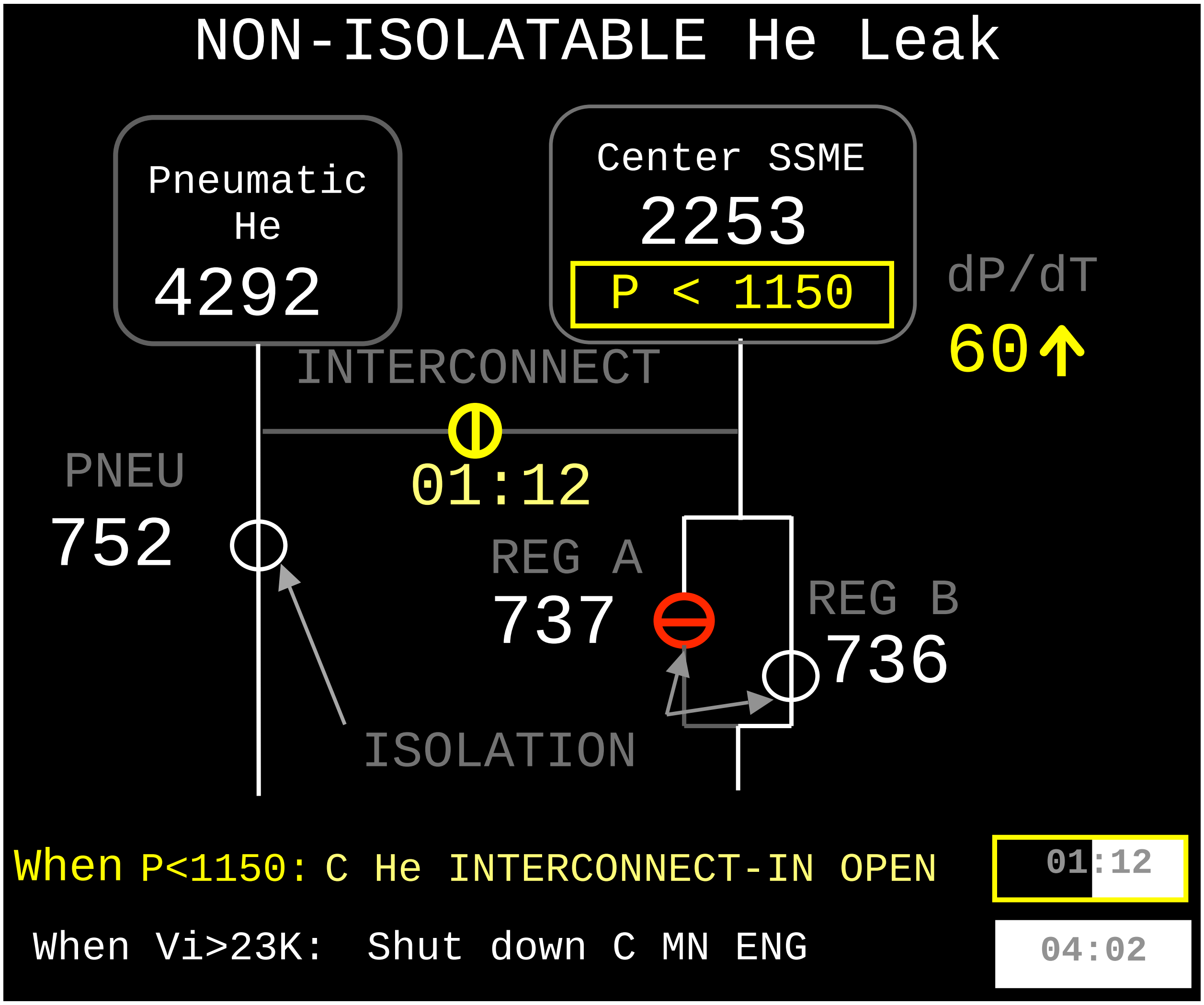

Figure 4. Candidate DASS Fault Management Display in “Countdown” Mode.

crewmembers and onboard automation, and places the greatest demands on user interface design. The primary requirement for the interface is that it enables and coordinates the “permissions-based” concept for procedure execution. Arguably the most obvious candidate for this interface is a dedicated fault management display patterned after the systems and fault management displays developed for the Boeing 777 and Airbus “A” series of glass-cockpit commercial aircraft. When a malfunction is detected on an A320, for example, the appropriate checklist automatically appears in written form in a dedicated (normally blank) section of the ECAM display page. In addition, a “systems synoptic” appears on a separate Systems Page. The synoptic depicts components of the system affected by the malfunction in a spatial layout designed to match the crews’ mental model of system architecture and system functioning. The crew completes each procedure manually, and keeps track of the status of each procedure (completed versus not completed) via a checkmark that fills a box to the right of each procedure, when completed. In addition, as the crew performs each procedure, the synoptic changes to display the new system configuration.

Figure 4 contains a prototype of a candidate fault management display that incorporates elements of both the electronic checklist and the “embedded-in-synoptic” formats, in a hypothetical DASS-equipped version of the shuttle. The display depicts a rather complex failure situation involving the helium supply system to one of the three (Center) engines that make up the shuttle’s Main Propulsion System. When an engine is operating nominally, helium flows out of the tank at the top of the figure and then splits into two redundant legs, each with a separate pressure regulator, before rejoining and flowing to the engine in question (where the helium continuously pressurizes a seal in the engine's high pressure oxidizer turbopump). Following the design criteria established by the CAU project, valves are depicted as circles containing an embedded line. When the valve is open, the embedded line is flush with the rest of the line, and the entire line is bright white, indicating that helium is currently flowing. We can see in the figure that the Isolation Valve for the right-hand (B) Leg is open and (as we would expect), helium is flowing through Leg B.

However, the symbol for the Leg A Isolation Valve is colored red, the interior line is perpendicular to the flow, and the Leg A line below the valve is colored dark grey (signaling no flow). Together, these indicators show that Isolation Valve A has failed to the "close" position. Critically, however, the figure also indicates a second failure in the system. The "dP/dT" value in the upper right-hand corner is colored yellow, which indicates that helium is being depleted at a higher than nominal rate from the tank, that is, the Valve A failure has been compounded by a leak somewhere in the helium supply system. This set of circumstances conforms to a "Non-Isolatable Helium Leak" condition, indicated at the top of the display, which is associated with two procedures. When the helium tank pressure (currently at 2253 PSI) falls below 1150 PSI, a manifold connecting the engine's helium supply system with a backup helium supply system must be opened, to keep helium flowing to the engine for as long a period as possible. Then, to avoid any chance of full depletion of the supply, the engine must be shut down when the vehicle reaches an inertial velocity of 23,000 feet per second. We assume that the DASS is capable of estimating the time remaining before both conditions will be satisfied, and also that the tank pressure will deplete to the target value (1 min 12 sec from the present) before the vehicle reaches engine shut down velocity (almost 4 min from the present). Thus, the "Interconnect Open" procedure appears at the top of a written procedures section (lower half of the display), and a "countdown" timer is provided just to the right of the written instruction. The timer currently shows 1 min 12 sec until this procedure should be performed. All information is written in yellow, to signal that the "Open Interconnect" procedure should not be performed immediately, but 1 minute 12 seconds in the future.

The schematic in the upper half of Figure 4 depicts the same information as the written procedure. The schematic is essentially a modified, zoomed-in version of the helium supply section of the CAU Main Propulsion System Summary Display, shown in the bottom right section of Figure 2. The schematic always depicts the current operational configuration, so the interconnect valve is shown in the closed position with no flow through the interconnect manifold. The procedural information is embedded in the schematic via size-and-color-coding: the interconnect valve symbol is enlarged and yellow, and a yellow countdown timer appears below the symbol. The color-coding signals that the upcoming procedure will command a change from the current (closed) position to the alternative (open) position.

As soon as the condition needed to carry out this activity is satisfied, the fault management display changes to "command" mode, illustrated in Figure 5. The countdown symbols disappear, and the interconnect valve symbol turns magenta. In parallel, the written procedure also turns magenta, and a virtual magenta "Accept" button appears to the right of the procedure. Again, referring to the schematic, magenta signals a recommended change from current (closed) to alternative (open) position. After appropriate review, the crewmember signals his or her agreement to proceed with the "Open Interconnect" procedure by touching the "Accept" button. Once DASS has performed the action (not shown in the figure), the "He Interconnect" procedure shifts down, and turns grey, and the engine shutdown line moves to the top of the written procedures stack. The schematic converts to a main engine synoptic showing the crucial valves that must be closed in order to achieve Engine Shutdown.

The "permissions" mode of human-automation interaction, and this user interface prototype, is designed to keep the crewmember in close synchronization with DASS and closely track DASS actions. On the upper (schematic) section, the mental exercise required to translate current valve position into the commanded position will further enhance situation awareness of the nature of the malfunction and the system configuration that will result from the recommended action.

Preserving Backup Capability with Head-Down Displays. This interface concept still contains a significant human factors drawback. Results of a recent study of shuttle fault management behavior by relatively novice operators (Huemer, Matessa, & McCann, 2005) provides strong evidence that

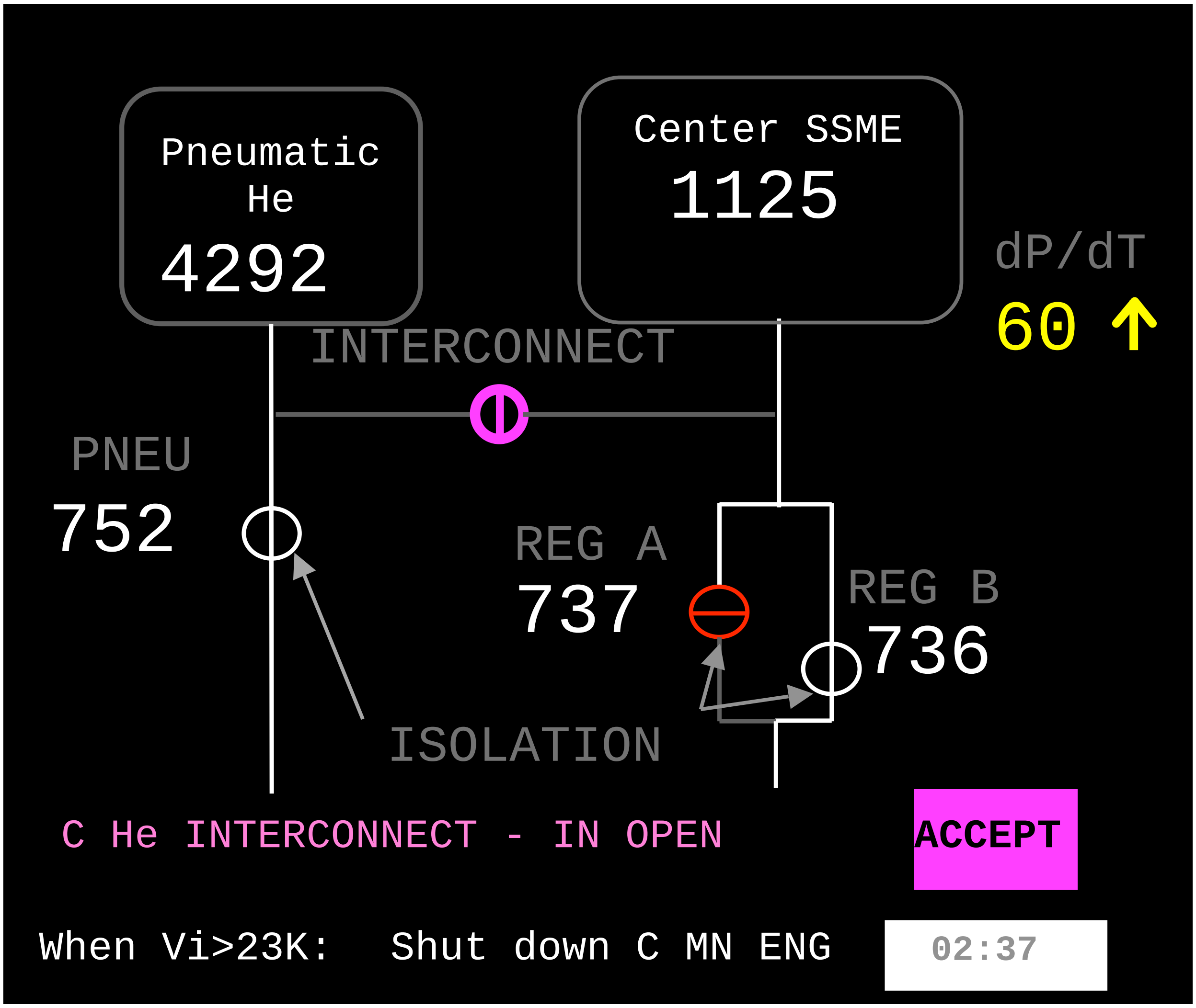

Figure 5. Candidate DASS Fault Management Display in "Command" Mode.

knowledge of the locations of the switch panels and their embedded switches plays an important role in enabling crewmembers to work malfunctions quickly and accurately. Because crewmembers are required to locate and throw the switches themselves, mission training in ground-based simulators continuously preserves and reinforces this knowledge. By contrast, the proposed system does not require crewmembers to physically locate the switches, potentially degrading their ability to do so in the event of a DASS failure.

Could we redesign the user interface to retain the benefits of automatic procedure execution and still preserve the crew's backup capability? One possibility might be to overlay each of the cockpit switch panels with a "head-down display", a (removable or retractable) layer of glass on which arbitrary forms of information and symbology could be superimposed on the panels. Since DASS performs the actual switch throws, the actual hardware switches underneath the glass panels would always remain in their "Computer-Controlled" position (usually, the middle position of a standard up-down switch configuration). The head-down displays would include "virtual" switch icons that depict the actual switch positions. When a procedure calls for a switch throw, the change could be signaled on the virtual switch panel via color-coding that makes the affected switch "pop out" at the observer from the virtual display. And, by having the "accept action" button appear right beside the commanded switch, the crewmember would be forced to orient to the location of the switch in the cockpit, constantly reinforcing his or her spatial representation of switch locations. The crewmember would therefore retain the knowledge to take over and throw the hardware switches manually, if required.

The idea of overlaying cockpit switch panels with glass displays has other potential benefits. Since all the hardware switches would be in (and remain in) the "Computer-Controlled" position, the physical switch panels would only provide information concerning actual (current) valve positions (e.g., open, closed, or in transition) if talkback indicators are present. The necessity to include a talkback indicator for every switch greatly increases the real estate requirements of the switch panels. If the switch panels were overlaid by head-down displays, the virtual switch icons showing actual switch positions would perform the function of the talkback indicators, greatly reducing the real-estate requirements of the physical switch panels.

Finally, by distributing procedural information across two separate cockpit locations (on top of the switch panels and on the dedicated fault management display), we would have a chance to build in some health management crosschecking similar to the crosschecking between the Primary and Backup flight software systems. We have already noted that reasoning systems come in many different forms. Suppose each systems-level health manager incorporated two distinct reasoning systems that worked redundantly and independently on root-cause determinations and fault diagnosis. One system could be generating root-cause fault determinations, and providing the appropriate procedures, on the fault management display. The other system could be performing parallel computations, also leading to the specification of the appropriate procedures, but depicting them on the head-down displays. Crosschecking the recommended procedures across the two display formats would enable the crew to assess the veracity of the information being generated by the fault management systems, and increase their trust in the recommended actions. The crosschecking requirement would also continuously reinforce crewmembers' spatial knowledge of actual switch locations, again helping maintain the spatial knowledge needed to execute procedures manually in the event of a complete DASS failure.

Crew-DASS Interactions on Longer-Duration (Exploration) Missions

Our candidate crew-DASS interfaces conform to current spacecraft design conventions by conveying all DASS information to crewmembers via visual displays, and restricting crew interactions with DASS to finger and hand (manual) interfaces. This standard approach to spacecraft cockpit design may simplify and streamline DASS development to the point where the system can be incorporated into the initial (Block 1) version of the Crew Exploration Vehicle (CEV; the replacement for the shuttle), scheduled to begin operations as early as 2011 or 2012. However, these conventional "input-output" channels will also force crewmembers to process DASS (and other flight and mission) information in small serial chunks (eye fixations) and, if more than one action is required, to execute each action strictly sequentially. Extensive laboratory research on human information processing limitations has also shown that more central cognitive operations, such as, for example, deciding whether DASS should be permitted to execute a procedure, are also carried out strictly serially. Even with DASS assistance, the "end-to-end" serial nature of fault management operations imposed by these interfaces will place clear lower limits on the time needed for a crewmember to resolve and complete the standard sequence of fault management activities. The interfaces will also virtually eliminate crewmembers ability to time-share malfunction handling operations on more than one malfunction at any one time. While emergency situations involving multiple overlapping malfunctions are rare, they are not unheard of. They pose a particularly clear danger during dynamic flight phases, when cognitive tunneling on fault management operations necessarily degrades situation awareness of vehicle flight path, attitude, and other safety-critical vehicle operations.

Fortunately, user interface technologies have advanced to the point where systems information can now be presented via auditory and even haptic displays, and machines can be operated and controlled by voice command as well as the more traditional manual interfaces. Studies have established the existence of a "preattentive" processing mode that extracts and processes information from all modalities in parallel and automatically directs focal attention to stimuli salient to the operator's current task set (Folk, Remington, and Johnston, 1992; Woods, 1994). It is also well established that people have considerable ability to plan and execute motor responses with their hands (automobile steering) in conjunction with speaking (Wickens, Sandry, & Vidulich, 1983). These findings suggest that crew-DASS interfaces involving these nontraditional modalities could increase the parallel processing capabilities of crewmembers, in effect boosting the human information processing resources available to work health management issues onboard the vehicle. These enhancements may not be critical for Block 1 CEV operations, when the vehicle will be confined to low Earth orbit and the crew will be able to rely on near real-time assistance from the ground. On later missions, when health management-related emergencies will have to be handled without such assistance, such interfaces could well make the difference between mission success and mission failure.

Therefore, in addition to considering traditional visual/manual crew-DASS interfaces, we need to consider Crew-DASS interactions via auditory and tactile channels. Malfunction warnings are an obvious target. An auditory warning can be designed to encode the degree of urgency of the problem, and 3-D audio technology can co-locate the perceived location of an alarm with the affected subsystem (thereby indicating the location of the threat) or with the visual fault management page (thereby quickly attracting crewmembers' visual attention to diagnostic information). Additionally, both auditory and tactile channels have been shown to be useful for presenting other types of data. Researchers have determined that humans can effectively extract useful systems status information from sounds that encode information relevant to systems operations, and that tactile feedback can be effective for informing a user about system state (for example, thruster operations can be conveyed through tactile elements ["tactors"] whose pressure on the skin maps to the current thrust level). Finally, natural language interfaces may be an effective method for time-sharing Crew-DASS communications with processing critical flight parameters on a visual primary flight display (PFD). For example, during a vehicle descent, DASS could communicate recommended procedures to a crewmember via a synthetic speech generator, and the crewmember could provide permission to perform the procedure via a speech recognizer, while the crewmember monitors vehicle attitude on the PFD.

Toward an Adaptive Cockpit. Earlier in the paper, we noted that automating fault management operations via DASS should be accompanied by a requirement, where possible, for crewmembers to act as a backup for DASS in case of hardware or software failure. We also made passing reference to the reverse case, where the automation would take over and accomplish functions that crewmembers normally perform. In our Crew-DASS functional allocation concept, this requirement would involve adjusting the automation level "upward" to the point where DASS would execute fault management procedures automatically, either after a time period elapses during which the crew can veto the action, or with no crew involvement at all.

Again, this kind of adaptive capability may not be a priority for Block 1 CEV operations, as mission durations will be short, crewmembers are likely to be functioning at a high level, and plenty of real-time ground assistance will be available. As missions increase in duration, however, requirements for adaptive capabilities are likely to grow. Crewmembers will experience long-term exposure to various space-based environmental stressors, such as circadian disruptions (fatigue), confinement, microgravity, and possibly elevated doses of radiation. During the quiescent (cruise) phase, minor performance decrements associated with these stressors may not pose much of a mission risk, as there are few situations where information processing and decision-making requirements are high enough to stress human capabilities. However, these quiescent periods are always followed by highly dynamic flight phases where, for a short time, crewmembers are called upon to manage and participate in activities that *do* place high demands on their information-processing capabilities. In a relatively recent interview, Neil Armstrong identified piloting and landing the lunar excursion module as the highest workload phase of the Apollo 11 mission (despite the fact that he was receiving near real-time assistance from the ground). To make matters worse, possibly the greatest space stressor of them all, an abrupt transition to a new gravitational environment, generally accompanies the abrupt transition to these high-pressure operational environments.

These stressors have considerable potential to reduce crewmembers' ability to perform effectively in high-workload situations. Therefore, depending on crew condition, it may be useful to flexibly adjust the

Crew-DASS functional allocation in order to decrease crew workload. The crew could make this determination themselves, of course, based on their own subjective determination of their current state and capabilities. Alternatively, sophisticated monitoring tools are currently under development that assess crew activities and performance patterns in real time, and make automatic determinations of crew workload and current cognitive function (Schmorrow & Kruse, 2004; Raley, Stripling, Kruse, Schmorrow, & Patey, 2005). The threshold for what type of fault management decisions requires crew input could be automatically raised or lowered depending on the real-time assessments of crew state and current workload. In addition, beyond their potential for enhancing crewmembers' processing capabilities, multi-modal displays could play a critical functional role in adapting Crew-DASS interfaces to accommodate real-time assessments. The system could flexibly determine which modality to use to notify the crew of a problem, for example. Research is currently underway to develop tools that can select the appropriate modality based on a model of the crew's real-time activities and a stochastic determination of how detectable information presented in a particular modality would be in light of current activities.

Usability Evaluations

Bringing advanced automation into the flight deck of commercial and military aircraft has generally enhanced operational safety margins. Frequently, however, the automation has emergent properties, not anticipated by designers, which negatively impact human performance to the point of opening up new possibilities for human error. These possibilities represent unacceptable risks for human spaceflight. Therefore, when developing an operational concept for a system, such as DASS, that automates many hitherto manual operations and carries requirements for completely new classes of user interfaces, it is crucial that a rigorous, thorough program of testing and evaluation be incorporated into the design process.

Traditional usability programs rely heavily on metrics such as the response time and accuracy with which test subjects perform overt manual activities, such as switch throws. Evaluating the usability of human-machine systems in which many of human activities become automated is a more challenging problem. There is less overt activity to measure, and a large proportion of the crewmembers' time is occupied by simply monitoring the functioning of the automated system. Accordingly, human factors evaluations of these systems have had to incorporate new, more covert measures of crew-automation interaction.

For example, this approach is embodied in the Intelligent Spacecraft Interfaces System (ISIS) laboratory at NASA Ames Research Center. The ISIS lab is currently configured to simulate a single-seat version of the Space Shuttle cockpit, but can be adapted to simulate a more general CEV crew-station environment, as necessary. Human-in-the-loop simulations have been completed of nominal and off-nominal shuttle ascent scenarios that include realistic systems malfunctions that must be identified and worked in real time. The lab records traditional overt behaviors, such as keyboard key presses and switch throws. However, as we just noted, these traditional measures of performance are not adequate to make the kind of fine-grained determinations of information acquisition and processing needed to evaluate crew-DASS interfaces. Thus, the laboratory also incorporates an eye-tracking system that records participants' gaze positions with high temporal and spatial resolution.

To illustrate the usefulness of eye movement data for evaluating systems such as DASS, consider the candidate fault management display concept illustrated in Figures 4-5. The fault management page represents DASS-recommended procedures in two distinct forms. The bottom half of the display provides the procedures in the traditional written form (checklist) common in today's glass cockpit aircraft. Following Malin, et al., (2000), the top half embeds the commanded procedures into the schematic of the affected system. The goal of this redundancy is to get crewmembers to crosscheck the two recommendations for consistency and accuracy of the automation, and enhance crew situation awareness of the overall fault management process. Eye-movement recordings during human-in-the-loop simulations will enable us to directly determine the frequency of such crosschecking, and thereby make direct (i.e., empirical) determinations of whether the design is meeting the functional goals of the designer, and of user preferences for one format or the other. These data will then be used to iterate on the design concept and optimize the features of the fault management display.

Usability testing in analog environments. Techniques that perform well in a spacecraft simulator can be further evaluated in a spacecraft analog environment. High performance aircraft, such as an F-18 military jet, share many characteristics with a spacecraft. Because high performance aircraft and spacecraft both are noisy, have a lot of vibration, and operate under high-G loading, the supposition is that there is a high correlation between usability of auditory and tactile displays in a high performance aircraft and in a spacecraft. In many situations, the workload of a fighter pilot is higher than that of an astronaut. Hence, the effectiveness of visual displays can also be evaluated in a high performance aircraft. Although systems in a high performance aircraft are not as complex as those of a spacecraft, arguments can even be made for testing the usability of proposed levels of automation and autonomy in the analog environment of a high performance aircraft. NASA ARC, NASA Dryden, and JPL are conducting an initial investigation of this hypothesis with the evaluation of ISHM systems on an F-18. Preliminary examination of this approach appears promising.

Summary and Conclusions

Replacing the shuttle with a new generation of crewed space vehicles gives designers a unique opportunity to enhance onboard health management capabilities with state-of-the-art health management software systems. However, there is no such thing as a free lunch. Making fundamental changes to "tried and true" health management operational concepts carries significant operational risks, cogently captured by the Johnson Space Center slogan "Better is the Enemy of Good." The way to ensure that "better" is a friend rather than an enemy is to adopt an operational concept for onboard health management in which the health management system becomes a team member, working fault management activities in close collaboration with the crew. The development of a successful "teaming" concept requires careful up-front analyses of the relative strengths that crewmembers and machines bring to bear on fault management operations, determination of a functional allocation, development of the user interfaces to support that allocation, and testing and evaluation of crew-system functioning in human-in-the-loop simulation.

We close with the observation that, even though the development process outlined in this paper is decidedly not trivial, there are broader considerations that dictate that health management software infusion should not proceed in a stovepipe fashion. There is some consensus that individual sources of information about subsystem state and functioning should be integrated into a more comprehensive "mission management" system with capabilities to perform cross-system and mission-level impact assessments of health-management-related decisions, such as ascent aborts. Such a system would require a higher-level "mission manager" that coordinates and integrates inputs from intelligent flight software systems and health management systems. Once again, to make such a complex knowledge engineering architecture functional, critical issues of human-machine interaction will have to be addressed. Suppose individual health managers (DASS systems) were all connected to a central mission manager. Where would control reside for issuing crew warnings and alerts? Should all off-nominal determinations from the system-level health managers go through the mission manager, so that it can act as a final "filter" to suppress false or nuisance alarms? In an adaptive cockpit, where would authority reside for who should (or should not) be alerted to an anomaly? The message from even these few questions is clear. Developers of advanced software systems should always keep in mind how their systems will interface with humans to accomplish mission goals and mission operations in a collaborative fashion.

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